Available online at www.sciencedirect.com
SciVerse ScienceDirect
ELSEVIER
Physics Procedia 36 (2012) 268 – 273
Physics Procedia

Superconductivity Centennial Conference

Integration of a cryocooler into a SQUID magnetospinography system for reduction of liquid helium consumption

Yoshiaki Adachi[a], Daisuke Oyama[a], Jun Kawai[a], Hisanao Ogata[a], Gen Uehara[a]

[a] *Applied Electronics Laboratory, Kanazawa Institute of Technology, Amaike 3, Kanazawa 920-1331, Japan*

Abstract

We are currently developing a magnetospinography (MSG) system for noninvasive functional imaging of the spinal cord. The MSG system is a device for observing a weak magnetic field accompanied by the neural activity of the spinal cord by using an array of low-temperature superconducting quantum interference device (SQUID) magnetic flux sensors. As in the case of other biomagnetic measurement systems such as the magnetoencephalography (MEG) system, the running cost of the MSG system is mainly dependent on the liquid helium (LHe) consumption of a dewar vessel. We integrated a cryocooler into the MSG system to reduce LHe consumption. A pulse tube cryocooler with a cooling power of 0.5 W at 4 K was placed adjacent to a magnetically shielded room and was directly connected to the thermal radiation shield of the dewar by an electrically isolated transfer tube. Cold helium gas was circulated between the cryocooler and the radiation shield. Consequently, the temperature of the radiation shield decreased below 40 K. Previous studies have shown that the detection of a weak magnetic field is often hindered by severe low-frequency band noise from the cryocooler. However, the band of the MSG signals is much higher than that of the cryocooler noise. Therefore, the noise can be filtered out and has a less detrimental effect on MSG measurement than on other biomagnetic field measurements such as MEG measurement. As a result, LHe consumption was reduced by 46%, with no increase in the noise floor.

Keywords: Keywords: SQUID, magnetospinography, cryocooler

1. Introduction

Functional information regarding the spinal cord is crucial for the precise diagnosis of spinal cord diseases such as myelopathy. A magnetospinography (MSG) system is a promising device for noninvasive functional imaging of the spinal cord[1]. An array of low-temperature superconducting quantum interference device (SQUID) magnetic flux sensors detects the transition of a weak magnetic field evoked by the neural activity of the spinal cord. The detected magnetic field is analyzed by using a magnetic source analysis based on spatial filter techniques, and then, the neural current distribution around the spinal cord is reconstructed and visualized. We can observe the delay and decay of the neural signal passing along the spinal cord by using MSG. The MSG system is an exclusive device that noninvasively provides such functional information regarding the spinal cord. In addition to conventional neurological testing and anatomical imaging by using magnetic resonance imaging (MRI) or X-ray computed tomography (CT), presurgical functional mapping of the spinal cord by using MSG will be crucial for the precise diagnosis of spinal cord diseases.

1875-3892 © 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of the Guest Editors.
Open access under CC BY-NC-ND license. doi:10.1016/j.phpro.2012.06.158

However, the running cost of the MSG system is mainly dependent on liquid helium (LHe) consumption, as in the case of other biomagnetic measurement systems such as the magnetoencephalography (MEG) or magnetocardiography (MCG) systems. High cost of LHe is often a large barrier to the introduction of the MSG system to a hospital.

Therefore, we tried to integrate a cryocooler into the MSG system by connecting it to the thermal radiation shield of the dewar to reduce LHe consumption. The thermal radiation shield was cooled by cold helium gas from the cryocooler, and this caused a decrease in the LHe evaporation rate in the dewar. This method is commonly used to cool the cryomagnet of MRI devices.

However, this method has rarely been applied to an MEG or MCG system. Magnetic noise from a cryocooler has a band of one or several hertz. It has a severe detrimental effect on MEG or MCG measurement. In contrast to the bands of MEG and MCG signals, the band of MSG signals is more than 100 Hz, and it does not overlap the band of the magnetic noise from the cryocooler. This finding suggests that the MSG system is highly compatible with a cryocooler.

In this study, we showed that LHe consumption can be reduced by cooling the thermal radiation shield of the MSG system. We also evaluated the noise level while the cryocooler was working.

2. Instrumentation

2.1. MSG system

The examined MSG system was a model similar to the ones described in several of our previous papers[2, 3]. The dewar was a double-layered vessel made of glass fiber reinforced plastic with a vacuum heat insulation. A thermal radiation shield made of copper was implemented so s to wrap around the inner shell of the dewar. The shape of the dewar was optimized for the measurement from the back of a subject in the supine position. It had a cylindrical main body with a capacity for holding 68 L of LHe and a part to hold a low-temperature SQUID sensor array protruding from the main body. The dewar also had a port for connecting a transfer tube to convey cold helium gas from the cryocooler system on the side of the main body, as shown in Fig. 1.

In this experiment, the sensor array was composed of 40 axial-type SQUID gradiometers arranged in an 8×5 matrix and placed in the protrusion of the dewar in a vertical fashion along its top surface. It covered an observation area of 140 mm × 90 mm. The baseline length of the gradiometric pick-up coils was 50 mm.

Every SQUID was driven by a flux locked loop (FLL) circuit based on the direct offset integration technique (DOIT)[4]. The FLL circuit used here is called a double-integrator-type with a band of 10 Hz – 12 kHz[5]. It was effective in removing the low-frequency band noise less than 10 Hz induced by the cryocooler system at the input of the preamplifier.

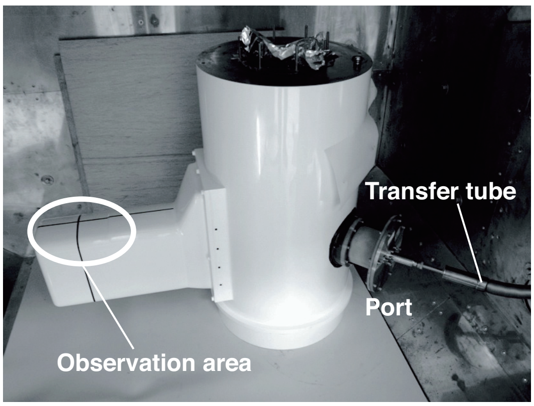

Fig. 1. Appearance of the dewar with a port for the transfer tube.

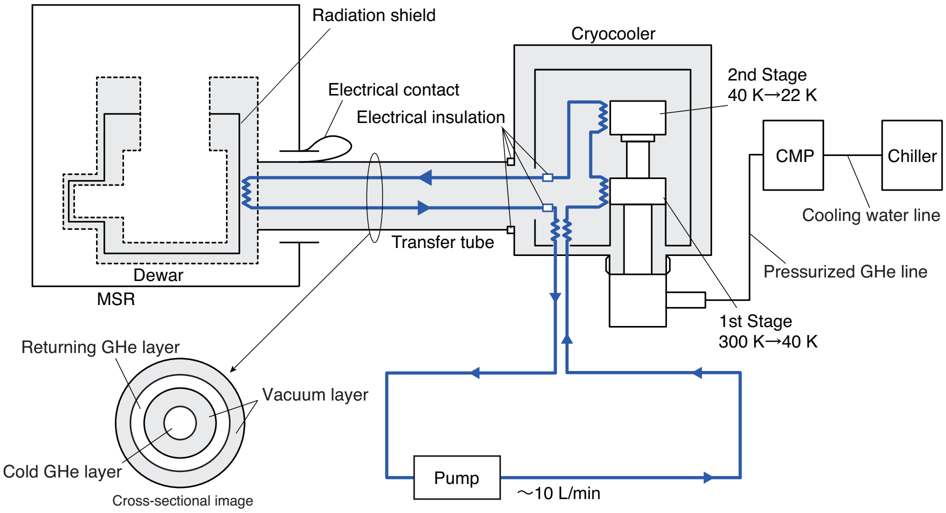

Fig. 2. A schematic diagram of the cryocooler system.

2.2. *Cryocooler system*

Fig. 2 shows a schematic diagram of the cryocooler for the MSG system. The cryocooler and the dewar were connected by a four-layer transfer tube. At the center of the transfer tube was a path for transferring cold helium gas from the cryocooler to the dewar. The cold gas line passed through the port and was tightly attached to the thermal radiation shield of the dewar. After thermal exchange, the helium gas returned through the outer layer of the transfer tube to the cryocooler. The returned helium gas was cooled down to 22 K by a pulse tube refrigerator with a cooling power of 0.5 W at 4 K (CryoMini PDX05/CW701; Iwatani Industrial Gases Corp., Japan). The helium gas flows in a closed circular line at a flow rate of 10 L/min. Therefore, the risk of contamination by atmospheric gases was quite small.

The dewar would be set on a gantry and be pivotally tilted in order to fit the upper surface of the protrusion to the dorsal part of a subject's neck. Therefore, the transfer tube was flexible and could be bent. The transfer tube was made of non-magnetic stainless steel. Electrical insulation was inserted between the transfer tube and the cryocooler to reduce electrical noise contamination during MSG measurement.

3. Measurement and results

3.1. *Liquid helium consumption*

As a preliminary examination, the transition of the LHe level was monitored before the installation of the cryocooler. After the installation of the cryocooler, the transition of the LHe level was monitored while the cryocooler was working. We completely filled the dewar with LHe and held it for one day for the initial cooling from room temperature. After the temperature of the thermal radiation shield was below 40 K, LHe was refilled into the dewar and LHe level monitoring was initiated.

Fig. 3 shows a comparison between the observed transition of the LHe level and the transition of the LHe level recorded before the installation of the cryocooler. The transition rate between 30% and 70% of the LHe level, which corresponded to the protruded part of the dewar, was evaluated. According to the gradient of the fitted lines, the LHe consumption rate of 13%/day without the cryocooler was reduced to 7%/day. As a result, the LHe consumption rate was improved by 46%.

3.2. *System noise*

Measurement of system noise was performed in a magnetically shielded room (MSR) with two mu-metal layers and one radio-frequency (RF)-shielding layer (MONOZ; Ohtama Co. LTD., Japan). The cryocooler

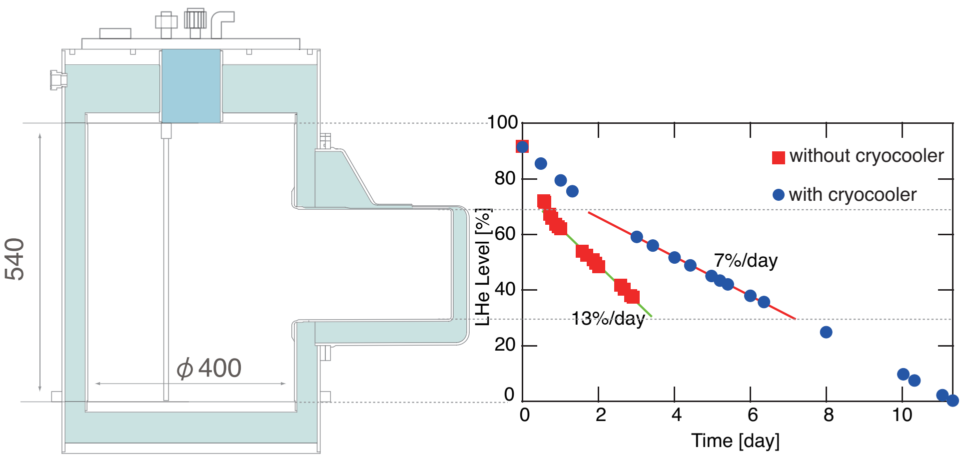

Fig. 3. Transition of the level of liquid helium.

system was placed 1.5 m away from the MSR. The distance between the sensor array and the cryocooler system was about 2.7 m. A compressor generating the pulse gas in the refrigerator, which was also a possible noise source, was placed about 6 m away from the dewar.

The transfer tube from the cryocooler was electrically connected to the RF-shielding layer of the MSR to prevent the tube from acting as a carrier for the external RF noise into the MSR.

The system noise was recorded while the cryocooler was working. All the signals from the FLLs were filtered using low-pass filters with a cut-off frequency of 5 kHz and digitally acquired at a sampling rate of 10 kHz.

Fast Fourier transform (FFT) analysis was applied to the corrected data obtained from each SQUID sensor to evaluate the system noise characteristics in the frequency region. Fig. 4(a) and (b) show the results of the noise characteristics acquired before and after cryocooler installation, respectively. In both figures, the average values from all sensors are plotted.

In Fig. 4(a), the 60-Hz component and its harmonics, for example, the 120-Hz, 180-Hz, and 300-Hz components, emerged from the noise floor. They originated from the commercial electric power. When the cryocooler was used, the 65-Hz component and many of its harmonics, for example, the 130-Hz, 195-Hz, and 260-Hz components, were additionally observed, as shown in Fig. 4(b).

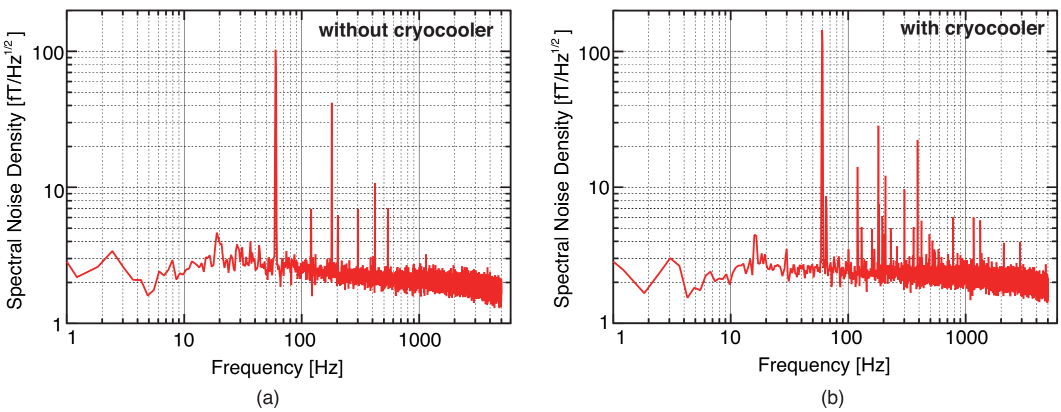

Fig. 4. Results of FFT analysis of system noise. (a) Recorded before the installation of a cryocooler; (b) recorded with the cryocooler working.

4. Discussion

The SQUID sensors retained their superconducting state until the LHe level went below 20%. Therefore, it was necessary to refill the LHe once in five days when the MSG system was operated without the cryocooler, as shown in Fig. 3. The cryocooler could extend the refill interval to more than one week. This is a practically large merit because once-a-week LHe delivery is easy to manage. From the perspective of operating an MSG system in a hospital, the LHe refill interval extended to one week is as good a benefit as saving LHe.

If a cryocooler system with a high-power refrigerator or with double refrigerators were installed to further reduce the temperature of the thermal radiation shield, more than 46% of LHe could be saved. However, when we discuss LHe saving, the other costs associated with the cryocooler must be considered. The electrical power consumption of the cryocooler system was about 7 kW, which was mainly used by the compressor of the pulse tube refrigerator. Water was also necessary to cool the compressor. The initial cost of installation of the cryocooler and the additional maintenance cost for the refrigerator must also be taken into account. The balance between the cost of LHe saved by the cryocooler and the other costs that increased because of cryocooler installation must be considered. This balance would often depend on where the system was installed, because the expenditure on electricity, water, and LHe always vary regionally.

The noise floor remained unchanged before and after cryocooler installation, even though small but many noise components appeared in the region of more than 100 Hz, as shown in Fig. 4. This indicates that the S/N ratio of the MSG signals obtained with the use of a cryocooler are as sufficiently good as that obtained without the use of cryocooler.

When the preliminary noise observation with the band from DC to 5 kHz was performed, there appeared a large peak of 40 $fT/Hz^{1/2}$ in height at 1.25 Hz in the noise characteristics plot (not shown). This frequency was similar to the frequency of activity of the pulse gas in the refrigerator. A pulse tube refrigerator is known to be a relatively magnetically silent apparatus, but the above finding indicates that the specific vibration noise caused by the cryocooler may contaminate the SQUID signals to some extent. However, this vibration would have no detrimental effect on MSG measurement because the band of the MSG signals is more than 100 Hz, and unlike the bands of other biomagnetic signals such as MEG or MCG, the band of the MSG signals does not overlap the frequency of vibration. Therefore, the double-integrator-type FLL could be applied to reduce the low-frequency band noise, including the vibration. Then, a noise floor similar the one acquired without the cryocooler could be obtained.

Subsequent noise investigation revealed that the peaks in the band of more than 100 Hz in Fig. 4(b) mainly originated from the inverter circuit used to drive the valve motor of the pulse tube refrigerator. Therefore, in the future, it will not be difficult to suppress them and further improve the data quality of MSG measurement with the cryocooler, because the source of noise is already known.

5. Conclusion

To reduce LHe consumption, a cryocooler system was integrated to the MSG system. The cold gas from the cryocooler reduced the temperature of the thermal radiation shield of the dewar. Consequently, the LHe consumption rate of the dewar was improved by 46%, and the LHe refill interval could be extended to more than one week.

The double-integrator-type FLL circuits effectively reduced the low-frequency band noise caused by the mechanical vibration of the cryocooler. The noise floor remained unchanged before and after the installation of the cryocooler, even though some additional components between 100 Hz and 3 kHz were found in the noise characteristics plot. This indicates that MSG measurement can be performed with sufficient S/N ratio.

Aknowledgement

We are grateful to Mr. Jun-ichi Fujihira for his great efforts and practical suggestions to complete the construction of the cryocooler system. This work was partly supported by the “CLUSTER” project, MEXT, Japan.

References

[1] Sato T, Adachi Y, Tomori M, Ishii S, Kawabata S, Sekihara K. Functional imaging of spinal cord electrical activity from its evoked magnetic field. IEEE Trans Biomed Eng 2009;56:2452–2460.

[2] Adachi Y, Miyamoto M, Kawai J, Uehara G, Ogata H, Kawabata S, Sekihara K, Kado H. Improvement of SQUID magnetometer system for extending application of spinal cord evoked magnetic field measurement. IEEE Trans Appl Supercond 2011;21:485–488.

[3] Adachi Y, Kawai J, Miyamoto M, Ogata H, Tomori M, Kawabata S, Sato T, Uehara G. A SQUID system for measurement of spinal cord evoked field of supine subjects. IEEE Trans Appl Supercond 2009;19:861–866.

[4] Drung D, Cantor R, Peters M, Scheer HJ, Koch H. Low-noise high-speed dc superconducting quantum interference device magnetometer with simplified feedback electronics. IEEE Trans Appl Supercond 1990;57:406–408.

[5] Adachi Y, Kawai J, Uehara G, Miyamoto M, Tomizawa S, Kawabata S. A 75-ch SQUID biomagnetometer system for human cervical spinal cord evoked field. IEEE Trans Appl Supercond 2007;17:3867–3873.